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1.—NOTES ON THE GEOMORPHOLOGY OF THE PELSART GROUP OF THE HOUTMAN'S ABROLHOS ISLANDS.

By

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I. INTRODUCTION.

(a) SCOPE.

My visit to the Abrolhos Islands came during the winter season, July, 1946, and most of the time was spent cruising in the great Pelsart lagoon, landing at one island or another and making reconnaissance surveys. Air photograpss by the Royal Australian Air Force are only available for Pelsart Island itself (called on the photos "Batavia Road Island," K.D.1028, numbers V.1772-1805, 9-12-43, 5-inch lens, 4,400 ft.), and for Gun Island (numbers V.1808-1809, same data as above). The only chart is a rather inadequate one of ancient vintage by the British Admiralty, called "The Houtman Rocks" (No. 1723), and on a scale of about $3\frac{1}{2}$ nautical miles to the inch.

Thus, although this material was all very valuable, I was forced to rely to a large extent on my own instrumental surveys. These were carried out by prismatic compass with pacing, a sufficiently accurate method for the size of islands involved. Elevations were measured by the eye-to-horizon method recommended by Kuenen (1933) for such coral island work; a check on this method, when used in appropriate areas, shows an error of much less than 1 in 10 feet.

In this way, sketch-maps were prepared of four of the islands in the Pelsart lagoon and other islands more superficially inspected. Three of these sketch-maps are reproduced herewith. (See text figs. 2, 4, 5.)

For some time I have been particularly interested in the influence of winds and wind-induced currents in the shaping and development of coral reefs. This study has been particularly stimulated by the examination of aerial photographs of such reefs during the war in the South-West Pacific (see Steers, 1945). I was then in charge of an Intelligence research section of the Royal Australian Air Force, and in particular made a special investigation of coral reefs, by land, sea, and air, in company with Dr. Curt Teichert and Dr. (then Lt./Col.) F. W. Whitehouse. Photo interpretation is not merely a great aid in unravelling the problems of the surface features, the geomorphology of coral reefs and islands, but also sheds light on other physiographic matters, such as the nature of prevailing winds and wave action. The pattern of the waves, often in intersecting series, is most instructive in explaining the shape and growth of coral reefs.

In contrast to these mainly constructional aspects of reef physiography, I have paid special attention to the destructive factors which tend to counteract the former. These are classified as biological, mechanical and chemical, the greatest of all being chemical, and a preliminary attempt is made to explain the solution of coral limestone by sea water under certain physical and biological conditions.

Finally, I have been on the look-out for evidence of old sea-levels, which in such a highly stable region as Western Australia during the recent epoch we would expect to be truly eustatic, without danger of distortion by isostatic or other local causes. I was not surprised therefore to find old marine benches and similar evidence at precisely the same levels as I had already observed at many points along the mainland coast.

From these particular studies, and from a general review of the physiographic position of the Pelsart Group, aided by the aerial photographs, the Admiralty Chart, and the results of previous workers, I believe I have been able to draw certain conclusions of general applicability.

As regards names, I have followed those found in the Admiralty Chart. Unfortunately, many of the smaller islands are without names, though some have had names bestowed upon them by the fishermen. In this way we have Post Office Island (formerly used as a cache for mail collection), Coronation Islets, Nook Islet, etc., in the Mangrove Groups, and I have marked these on the map; others here are known temporarily after the fisherman, or his vessel, customarily based there,

e.g., Charlie's Islet, "Maori Lass" Islet, but as these appear to have no lasting validity, I have not included them.

On an old sketch-map preserved at the Lands Department, Perth, numbered O.P. Eng. 235, there are quite a number of these small islets with names. They include "Wreck Island" (at the south end of Pelsart Is., referred to by Teichert as "Little Island"), "Jubilee Island" (now known by fishermen as "Stick Island"), "Nought Island" (now known as "Green Island"), and a group of islets lying between Middle Island and Rat Island, numbered from "One" to "Eight." Only these latter have I incorporated in my map (see text fig. 1). There is also a "Post Office Island" on the Lands map, but this corresponds to what the fishermen at present call "the Nook" or "Nook Islet."

Grateful acknowledgment must be made to Mr. Keith Sheard, officer of the Division of Fisheries, of the Australian Council for Scientific and Industrial Research, who organised the trip, the success of which was largely due to his excellent companionship and his introduction to our able skipper, Mr. Jack Basedon, of the "Maori Lass." Expenses were defrayed by a university research grant from the Commonwealth Government. Skilled assistance with the drafting was provided by Mr. Henry Coley.

(b) PREVIOUS WORK.

Earlier workers have concentrated their attentions mainly on the biology of the reefs or on the geomorphology of the larger islands. Little or no work has been done hitherto on the smaller islands that dot parts of the Pelsart lagoon and fringe its northern border.

The Admiralty hydrographic surveyor, Captain Wickham, already over a century ago noticed the difference between the flat, tabular limestone of some of the islands in contrast to the loose coral detritus and shells of certain other islands (1841). Saville-Kent in his "Naturalist in Australia" (1897) made a notable contribution in his description of the growth of a coral island from an initial accumulation of such debris on a reef near Gun Island.

Dakin (1919) contributed a valuable general description of the islands and their reefs, classifying them, incidentally, as evolutionary steps on the way to becoming atolls. The latest work is by Teichert in his "Contributions to the Geology of Houtman's Abrolhos" (1947*a*), the results of his careful surveys there in 1944, some of which he was later able to interpret in the light of our joint experiences, both on the ground and in the air, in the Great Barrier Reef area in 1945.

This work of Teichert's is the first strictly geological and geomorphological study of the Abrolhos and is one of the most valuable and complete that has ever been accorded a group of coral islands. I shall, therefore, make many references to this pioneer study, and many of my own observations may now only be regarded as amplifying and confirming his own. It should be added, however, that I did not possess his detailed maps or complete manuscripts when I visited the islands, so that these observations were for the most part independent of his.

Another paper of Teichert's, on Rottnest Island (1947*b*), was also in the press at the time of my visit, and is now particularly valuable for correlation of eustatic levels.

Earlier references to the work of wind in controlling the geomorphology of coral reefs may be found in most of the classical works on coral reefs from Darwin (1842) onwards. Wood-Jones (1910) was a particularly clear exponent of this subject, following upon his experiences in the Cocos-Keeling Islands. More recent observations may be found in Umbgrove (1929) for the Java Sea area; in Kuenen (1933) for other parts of the East Indies; in Krempf (1929) for the South China Sea; and for the Great Barrier Reef area, in Stephenson, Tandy and Spender (1931), Spender (1930), Steers (1929, 1937, 1938), and in papers by Fairbridge and Teichert (in the press).

(c) Winds.

On my visit to the Abrolhos in July, 1946, I was singularly fortunate in being able to observe the effects of wind from almost every quarter. During that period a regular series of cyclonic disturbances were crossing the south-western part of the continent. The normal south-westerly winds, which blow for much of the year in this region, would generally back steadily to south, south-east and east, when there would be a day or two of calm and sunshine with a slight land breeze. Then it would back quickly to north and blow a gale from the north-west for several days; and then the process would be repeated at longer or shorter intervals.

Normally speaking, it may be said that on the average the southerly is the prevailing wind. During the three or four summer months (December-March) when these latitudes are affected by the tail of the trade-wind belt, it blows very steadily and with considerable force, from practically due south to south-south-east (the "Southerly Buster"). Gales of considerable violence come from north-west in the winter season. Milder south-easterlies are fairly common in the autumn and while storms from the north-east are rare, they exert a considerable effect on the unprotected northern islets.

(d) Tides.

Coastal geomorphologists are becoming more and more conscious of the importance of tides in the local control of physiographic features. At the 25th A.N.Z.A.A.S. Meeting at Adelaide in August, 1946, with E. D. Gill, I made a special appeal that tidal figures be always included in coastal geomorphological studies. It is thus most unfortunate that we do not possess the appropriate data for the Abrolhos.

The Admiralty chart records a spring tidal range of $2\frac{1}{2}$ feet. There have, however, been no really scientific measurement of tides in the islands at all, and this figure is most certainly too low. On Pelsart, Teichert estimated that the range would be over 3 feet. While at the Mangrove Islets in the northern part of the Pelsart group, I came to the conclusion that the spring range was very close to 3 feet 6 inches. This figure represents an actually observed spring range in July, 1946, and also coincides with the calculated figures based on physiographic levels (see below).

It would, of course, be extremely valuable if continuous tidal records could be obtained by a mechanical tide gauge. On the other hand, however, fairly close estimates of maximum spring range can be obtained in coral islands by the following indications:—

(i) First, the lowest spring tides will drop to a few inches, and no more, below the growing coral colonies. A very large percentage of the contemporary reef-level does not vary more than 1 foot above or below the level of low-water springs. That precise level can generally be observed by the dead tips of the *Acropora* fans, which grow up high during periods of neap tides and then get killed down by exposure at springs (see Plate I, figs. 1, 3 and 4). In non-living reef areas it may be observed that low-water springs is the absolute base-level of subaerial erosion, and in certain protected places this can be quite accurately judged.

(ii) Then secondly, the height of maximum tidal range can be observed in protected lagoonal areas by the blackening of the dead coral. Again, this is the maximum height for the sea-water corrosion of calcium carbonate. In protected areas, the maximum chemical erosion of the limestone will be exactly at mean sea-level. Teichert has also noted this correspondence between the deepest undercutting of the cliffs and mean sea-level.

It may be seen thus that our elevations are really of quite a high order of accuracy, within a very few inches, although not founded on instrumental records. It is not argued that this is perfectly satisfactory, but it is certainly of great value for work in the nature of a preliminary reconnaissance.

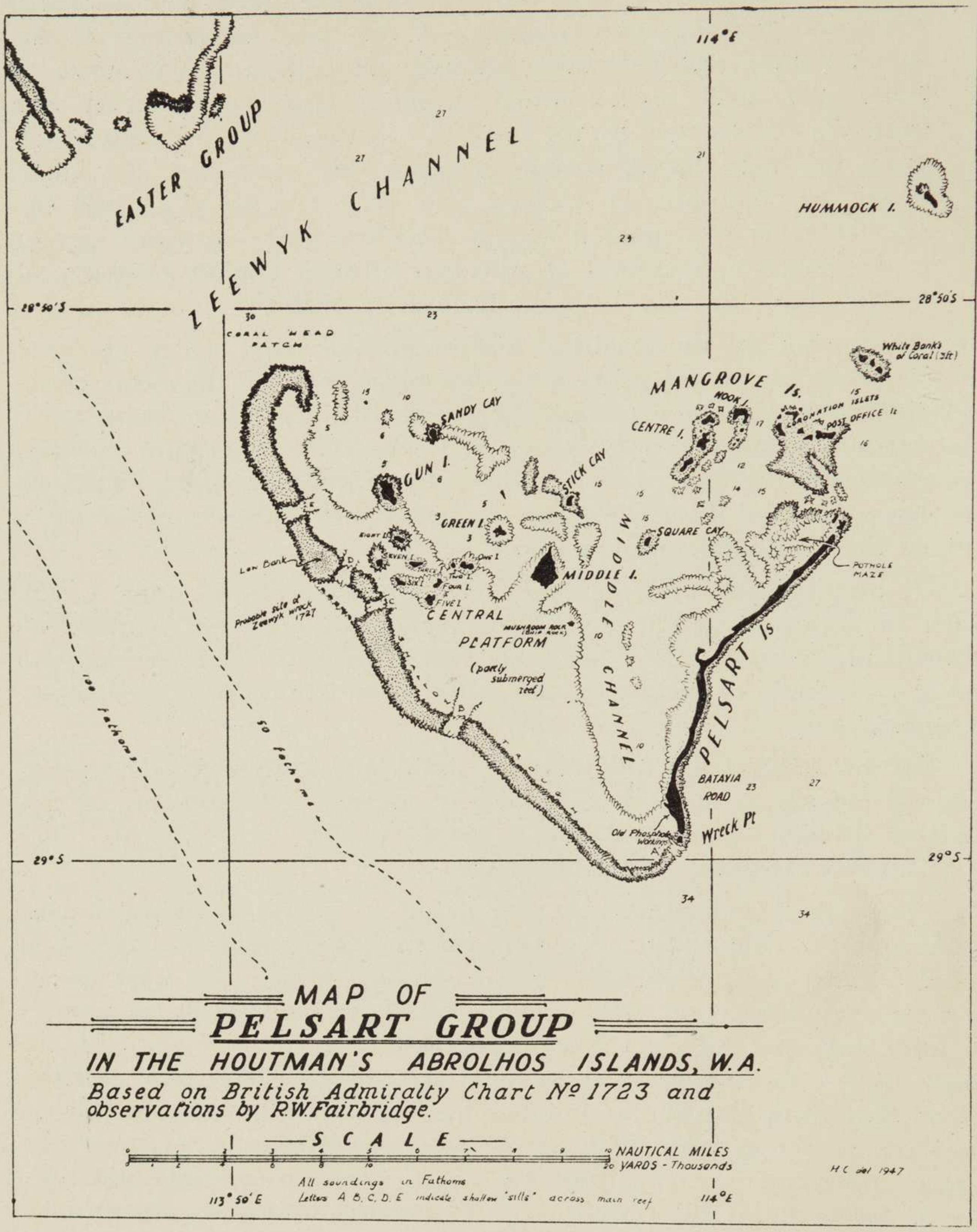
In this work I am following the usual Admiralty method of referring all heights to mean low springs as "datum." Advantages of this method I have already outlined (with E. D. Gill) at the 25th A.N.Z.A.A.S. Meeting (Adelaide, 1946).

The actual periodicity and time of tides is of no geomorphological significance, of course, but a few notes on the subject may be of practical value. Local enquiry showed that maximum spring tides, such as are best for examining coral reefs, occur generally in daylight in the months of June, July and August. They correspond then more or less with the lunar cycle. It is interesting to note that, while Dakin and Teichert found that from October to January the best low tide was generally in the early morning, I found in the opposite season that it was generally late in afternoon (varying from 3-6 p.m.). In any case, abnormalities are as frequent in this region as at Fremantle, where, as observed by Curlewis (1915), the lunar-controlled movements of the tide are often modified by the prevailing wind and barometric conditions.

II. OBSERVATIONS.

(a) THE BASEMENT.

The Pelsart, or Southern Group of the Abrolhos Islands is, according to both Dakin (1919) and Teichert (1947), the oldest and most mature of the Abrolhos reef complexes. It stands on a platform of about 25 fathoms depth, which connects it with the other islands and with



Text fig. 1. Map of Pelsart Group.

the mainland. It is possible, however, that the base of the coral may even be traced down to the 40 fathoms line. On the outer side, the south-western face of the group closely parallels, at a distance of 6-7 miles, the edge of the continental shelf, which hereabouts follows very approximately the 100-fathom contour (see text fig. 1). (1)

Superimposed on the south-western border of the 25-fathom platform, the Pelsart Group rises in a massive triangular block, sloping very steeply away to SW and SE, but much more gently to the north. A number of isolated reefs also rise from the 25-fathom platform in a north-easterly direction—the "Coral Patch" ("white banks of dead coral" of the Admiralty Chart), King Reef, Hummock Island (a sand cay 500 yards long and 16 feet high), Mid Reef and other lower patches where the swell may be seen breaking occasionally.

This massive coral reef platform is bounded by continuous reefs all along the south-west and south-east sides, and by scattered reefs and islets along the north side. The central lagoon is partially of deep water (10-15 fathoms) but is mostly blocked by reefs. The general impression is that of a *compound atoll.*

Darwin in his classical work "On the Structure and Distribution of Coral Reefs," on the basis of Wickham's survey, hesitated to class it as an atoll on account of the "extreme irregularity," but as Dakin (1919, p. 177) has already pointed out, the Pelsart Group is far from irregular, and appeared to him to be an atoll. Teichert (1947, p. 191), on the other hand, held that this view is untenable owing to the presence of old reef cores. In my opinion, however, this feature is merely attendant on the long and variegated history of the Abrolhos and might perfectly well be associated with any reef which began as a simple atoll, but which experienced a similar complex evolution.

One could use Davis' term "bank atoll" (1928, p. 19). Bank atolls, according to Davis, are "bank reefs, which rise back from the outer margin of rimless shoals." If the reef is annular then it is a "bank atoll." Clearly, Davis included the continental shelf in the "rimless shoal" category and therefore (*op. cit.,* p. 204) classified the Abrolhos as "a former bank atoll, uplifted and now in process of degradational transformation into a new sea-level atoll in the manner proposed by Agassiz (1899, p. 135)." Since Davis often used "bank" and "shelf" in the same sense, we might perhaps speak of it better as a "shelf atoll." Teichert himself preferred to translate the Dutch "plaatrif" (of Niermeyer) as "shelf reef" (1947*a,* p. 191), and there is no doubt that this is clearer than any vague term using "bank" or "shoal."

I should like to re-emphasise the fact that the Abrolhos reefs are not of the mid-Pacific type (where Darwinian subsidence appears to play a major rôle). Rather they are reefs built on stable foundations, and have suffered complex eustatic evolution. As Voeltzkow (1907) and

(1) Teichert noted irregularities in the soundings here, but it is clear that certain of the earlier soundings on the Admiralty Chart are badly misplaced, and in all probability the continental edge in front of the Pelsart Group seems to be nearly rectilinear in a NW-SE direction.

others have already observed for most of the Indian Ocean reefs, their cores do not consist of recent reef corals for the most part, but of various older lagoonal sediments and of old down-planed reef limestones, on which the contemporary corals grow "like flowers in a garden."

(b) The South-Western Reef.

On the south-west side, this approximately equilateral triangle is bounded by a typical ribbon reef of the barrier type, with symmetrically inwards curving extremities—the type which may be seen again and again over hundreds of miles along the outer edge of the northern section of the Great Barrier Reef of Queensland (see Stephenson, Tandy and Spender, 1931). The south-west barrier is 12 nautical miles in length, and over it the heavy south-west swell from the Indian Ocean may be seen continuously breaking. From a central point, such as Middle Island, which lies nearly 4 miles within the outer reef, it is possible to stand on a high tower and observe the wonderful spectacle of that wall of breakers and spray, rising continuously to 50 feet and more, through an arc of over 150° on the compass (see photograph, in Saville-Kent, 1897, p. 132). The width of the reef varies from one to several hundred yards, but the level is low, ranging from 1-5 feet, though it is sometimes possible to walk along sections of it at low tide, when the surf is not too great.

At certain points there are low shingle banks, as for example, opposite Gun Island, which rise a few feet above the general level. Scattered along the reef are dead coral boulders ("negro-heads") of various sizes. Many of these are loose and have merely been cast up by storms (the "jetsam" type described by Saville-Kent, 1893, and others), but others consist of old coral limestone *in situ* and with under-cut margins which are obviously solution relics (as observed long ago by Dana and Agassiz, later by Gardiner (1931), and here in Pelsart Group by Teichert (1947*a*), proving once again that there are two sides to every argument!).

At high tide the sea pours over the outer reef at almost all points and sweeps into the lagoon. Dakin (1919) has compared it with a "huge natural weir." A maximum volume of water converges from west, south and east at the south-eastern extremity, pouring over a "sill" there, somewhat lower than the rest of the reef. Aerial photographs show how the newly abraded sedimentary debris is being washed from the outer edge of the reef here, northwards into the lagoon, where there is an ever-fresh cone of new sediment (see, for example, the air photo reproduced by Teichert, 1947*a*, Plate VII, fig. 1).

Mr. Keith Sheard, who has flown all along this south-western reef, has kindly informed me that there are no less than five of these "sills," even deeper than the southern one, distributed along the reef. Their position he has delineated on our map. The water pours over them, partly into channels on to and across the Central Platform and partly into a shallow trough or gutter around the inside margin of the reef (see text fig. 1).

This south-western barrier might appear to be a typical example of the characteristic product of a dominant swell and wind direction,

which on this coast is from the south-west. On the Great Barrier Reef, in contrast, the wind is dominantly south-east, but in that case the trend of these ribbon reefs are not at right-angles to the wind direction, and it may be concluded from the bathymetric evidence that the primary orientation of such reefs is due rather to the trend of the underlying shelf topography. As noted in the preceeding section, the south-western reef closely parallels the NW-SE trending shelf edge.

(c) THE SOUTH-EASTERN REEF AND PELSART ISLAND.

On the south-east side of the triangle there is a long sinuous island-capped reef, extending from the south-east "tail" of the outer barrier, away to the north-east for a distance of over 6 miles. This is Pelsart or Long Island (also called Batavia Road Island). It has a core of hard coral limestone rising to 18 feet above datum, and is superimposed by a complexity of younger deposits. (For a very complete description of the island, see Teichert, 1947*a*).

The island has no exact counterpart elsewhere in Australian waters, but may perhaps be compared with the raised margins of some of the larger Pacific atolls, of the Cocos-Keeling Group, or of compound atolls such as those of the Maldives, etc., in the Indian Ocean. The difference, of course, is that all those examples are situated on mid-ocean banks, while the Abrolhos rise from near the edge of a continental shelf.

This south-eastern face of the group is fully exposed to severe storms, but the main swell breaks along it after swinging about the southern extremity, around 90° from the south-west. In addition, the tail end of the south-east trades is felt here all through the summer. The controlling factor, however, is the south-westerly swell. Debris would have accumulated all along this south-eastern margin of the reef platform, but mostly just at the tail of the south-west barrier (about Wreck Point). From here the material would have been "shepherded" along to the north-east under the combined influence of the deflected waves of the south-westerly swell, breaking obliquely along the south-east side, and of the small waves, locally generated by the south-west wind within the lagoon, which would break obliquely along the north-east shore of the island. An analogous process has been observed in the building of long shingle tongues on the island reefs of the Great Barrier Reef lagoon.

(d) THE NORTHERN REEFS AND THE NORTHERN ISLETS.

Turning now to the third, or northern side of our triangle, we find a 10-mile sector of very irregular reef patches, both large and small, which in places are interfingered by a complicated network of deep channels (some exceeding 15 fathoms). These are coral reefs typical of fairly calm water conditions (Marshall, 1931). Many of them are crowned by small islets, some of fairly ancient origin, such as the Mangrove Islets, and others, such as Square Islet, Stick Islet, Sandy Islet etc. are merely shingle and sand cays of comparatively recent origin.

A study of the weather conditions quickly brings a partial explana-

tion for the irregularity of these reefs. For the greater part of the year this northern side is entirely protected from the southerly gales and from both the south-westerlies and south-easterlies. During the winter season, there are also storms of considerable violence from the north-west, and more rarely from the north-east. The force of the former may to some extent be broken by the presence of the Easter Group and the Wallaby Islands, which lie to the north-west. Nevertheless, at these times, as well as with westerly and south-westerly winds, a moderate swell is felt in the Zeewyk Channel and heavy surf may be seen along the northern edges of these reefs. The result is the accumulation of low shingle banks (not over 2 feet high) and small negro-heads (up to 3 feet only in diameter) along these northern rims.

Similar, but still lower shingle banks may be observed at low tide around the southern margins of those reef patches which are exposed to a few miles of "fetch" in the lagoon area. Even over such short distances a stiff gale may whip up sufficient waves to throw up fragments of the fragile coral species on to the reef edge (see Plate I, fig. 1). This is particularly well seen in the south and east of Stick Island.

Evidence from the plans of the old beach ridges of the Mangrove Islets etc. shows that at periods of higher sea-level these islets were less protected from the westerlies than at present, and high shingle banks were built up, with the typical incurving spits at each end which are so characteristic of shingle breastworks in the Great Barrier Reef and the Java Sea areas. True "ramparts" of asymmetric section are scarcely known, however.

An additional factor to wind, in the shaping of the northerly rim of reefs and islets, is that of tidal currents and scour. While the considerable irregularity in the detail of these reefs has been noted, a rough north-south orientation can be detected when viewed on the broad scale. This north-south alignment, by analogy with such cases as the Torres Straits reefs, may be interpreted as due to currents.

At the Pelsart Group it was observed that with the rising tide the current sets southward, into the lagoon through all the northern openings, while the falling tides sets to the north. These northern channels are the only exits for the whole lagoon, but especially at high tide a considerable body of water breaks over the twelve-mile section of reef in the south-west and enters the lagoon from that direction. This water tends to bank up with the rising tide, but augments the ebb tide very considerably, both in strength and duration. In this way a 2-3 knot northward current is often observable over extended periods at the northern openings.

Of all this evidence, none, however, appears to be adequate by itself to explain the obvious irregularity of the Northern Reefs, intersected as they are by 15-fathom channels. No such major breaks are found in the south-westerly and south-easterly reefs. These features appear to be beyond the control of the contemporary forces of growth and erosion, and thus we turn to events in the geological history of the group for the basic explanation (see Section III).

As noted above, the islets of the Northern Reefs are of two types, older ones of coral limestone material, and very recent ones of loose sand and shingle.

Of the former, let us take one of the *Mangrove Islets* as an example. These lie in the north-east part of the group and consist of about a dozen low islets, not more than 12 or 13 feet high, and 200 or 300 yards in length, and highly irregular in shape. They are all mainly of old coral limestone and surmounted by shingle beach ridges. They have little vegetation save for the mangrove patches that their name implies. In the west there is a group of three trending north-north-east, and for convenience I have called the middle one *"Centre Islet"* (28° 52½′ S., 113° 59½′ E.).

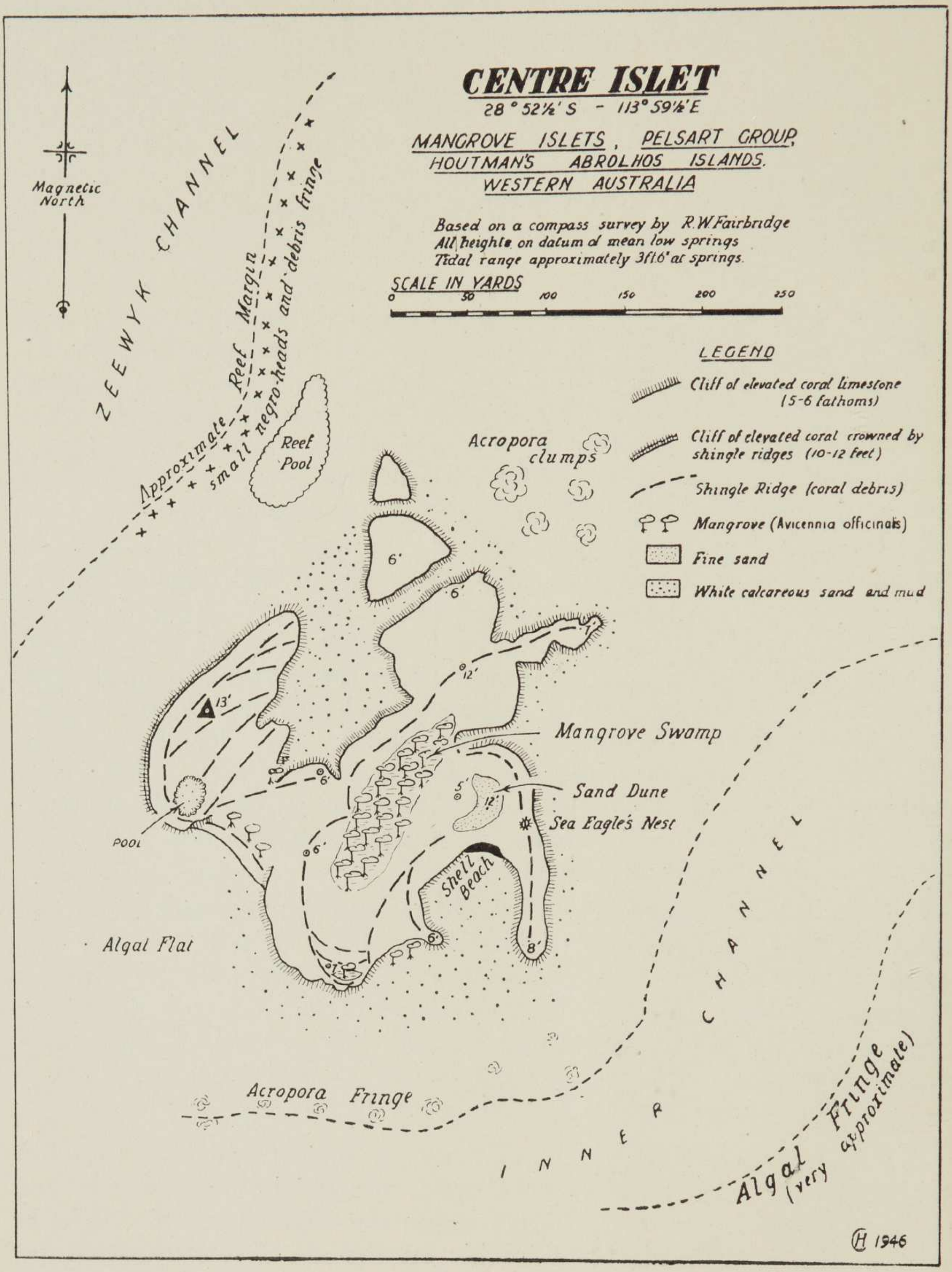
The islet is 300 yards long and an equal distance across, but with deep indentations so that its total area is not great (see text fig. 2). It consists fundamentally of a core of old coral limestone (mainly heavily branched *Acropora* species and coralline algæ) which stands in a uniformly cut platform at 5-6 feet above low-tide level. Most of its outline is marked by 5-foot cliffs of this rock. It is very hard and in many places the cliffs are deeply undercut by the sea.

There is a small, circular pool or "pot-hole" 25 yards across in this platform near the western edge which fills at high tide by the sea filtering through the loosely cemented coral limestone. Even the inside cliffs bounding this pool are undercut (proving, if proof were needed, that the undercutting can have nothing to do with mechanical wave erosion). It is floored with a carpet of sticky white calcareous mud. A rather similar depression runs down the length of the islet, but is filled with mangrove (*Avicennia officinalis*). The same mangrove (which is fairly stunted in these islets, rising only to 20-25 feet) also occurs in small patches around the cliff-line, but is here and there overwhelmed by shingle invasions.

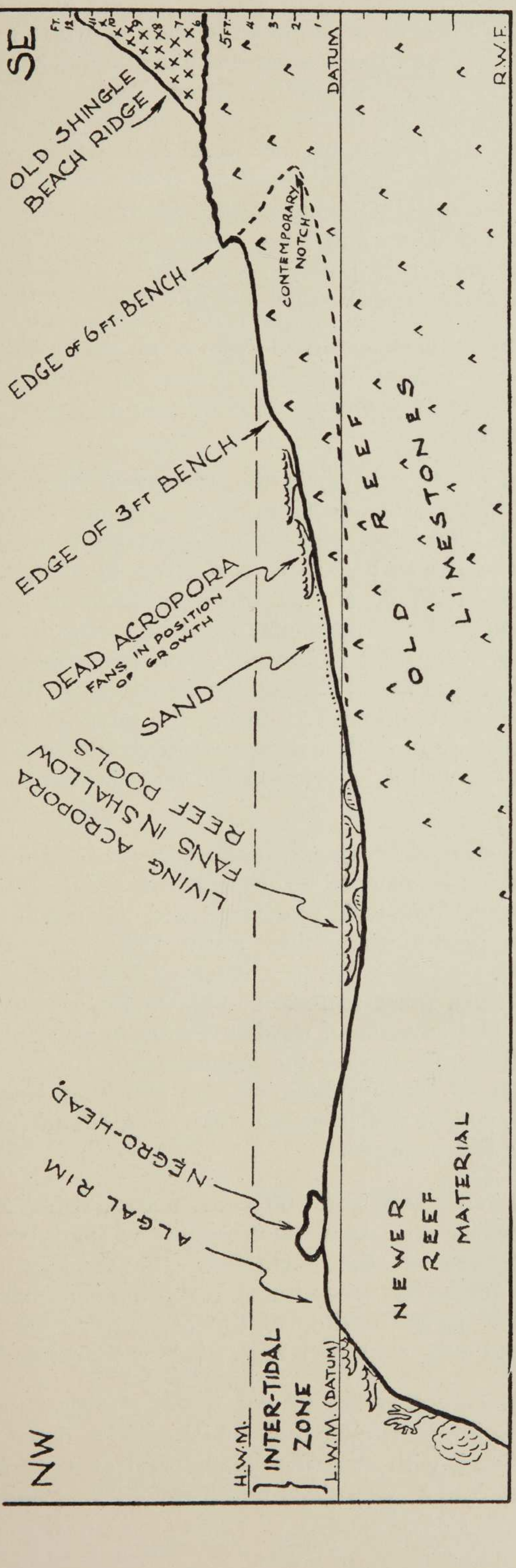
Over the surface of this platform are distributed series of ancient shingle beach ridges (mainly of flat, platey *Acropora* fans, together with short, stumpy lengths of branching types, just as described by Teichert (1947*a*, p. 154). In plan these ridges trend NE-SW, parallel to the exposed reef margin to the north-west, and their extremities curve away to the south-east. These old ridges rise to 12 and 13 feet. There is also a small (contemporary) sand-dune in the east part of the islet.

Contemporary shingle invasions lap up against and over the cliff-line in places in the north-west and west, to a height of about 6-7 feet. In certain places these newer beach ridges are themselves suffering wave erosion; this is particularly noticeable on the south-westerly, the most exposed of this little group of islets.

In places, a lower bench level may be observed in these coral limestone cliffs. This bench stands at about 3 feet above datum and is itself sometimes cliffed and undercut. From below this bench dead *Acropora* fans (of the very shallow-water type) in position of growth may be traced from about 1 foot 6 inches down to datum. The gradational aspect of this feature suggests that the latest drop in sea-level has not been a sudden one (see text fig. 3).



Text fig. 2. Sketch-Map of Centre Islet.



Text fig. 3.—Section, somewhat idealised, on the weather side of the Mangrove Islets. The basement consists of old reef limestone, probably with a veneer of newer reef material on the outer edge. Erosion benches have been left by the former sea levels at 5-6 feet and 2-3 feet. In many places, all trace of the 2-3 foot level is destroyed by the formation of a contemporary bench and undercut notch.

Almost all around Centre Islet and likewise around other members of the Mangrove Islets there are widespread patches of white calcareous mud on the reef-flat itself. There is generally no living coral within about 50 yards of the shore. From the severe undercutting of the cliffs and deep indentation of the shores it seems to be undeniable that these islets are in the process of very rapid destruction. That the erosion is by chemical solution in the sea-water is shown by the restriction of the effects to the intertidal zone and by its equal, if not greater, effectiveness in protected coves and bays. Since many of the smaller islets occur on continuous reef patches, we may well conclude that they have been isolated from each other by this means.

Thus, while there is vigorous coral growth in the outer parts of the reefs here, the inner sections, especially where the white calcareous mud has accumulated, most probably represent down-planed areas of former old coral limestone.

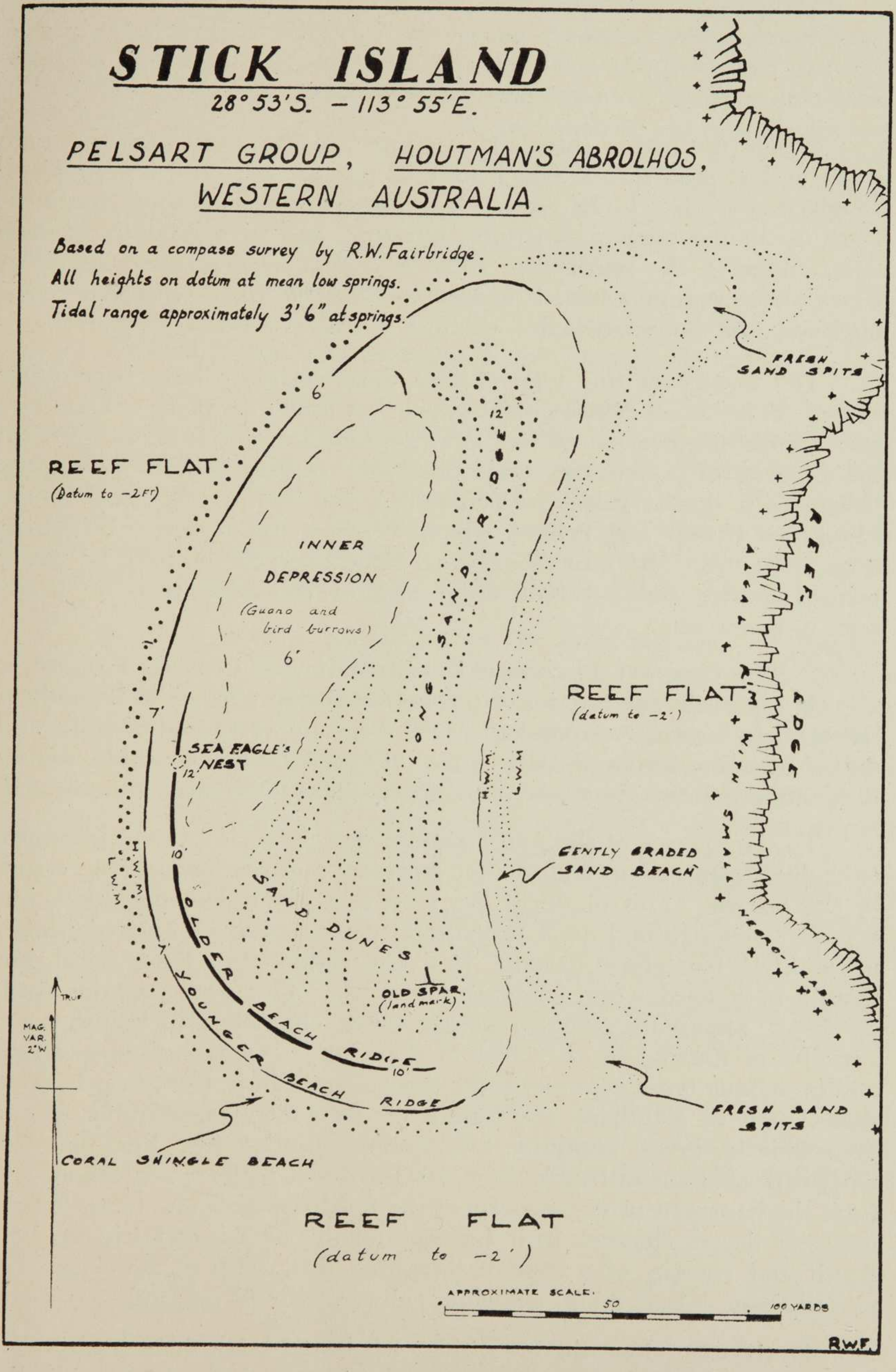
Clearly, the geological evidence in the Mangrove Islets suggests a somewhat variegated history. There is no direct evidence for ascertaining the age of the coral limestone, but by analogy with Teichert's work on Pelsart Island we might well place it in the late Pleistocene. There is, however, no obvious example of the 10-foot mid-Recent bench here and it may possibly be that this particular coral limestone in the Mangrove Group is younger than the Pleistocene coral limestone of Pelsart. In this case it could have formed during the mid-Recent 10-foot high stand and in any case became benched during the later 5-6 foot stand. (It may be remarked in passing that these two levels are so widespread in Western Australia, as well as overseas, as to be regarded as probably eustatic.)

The 5-6 foot bench next became partially covered by shingle beach ridges, as the sea gradually dropped to its next still-stand. (In Pelsart this would be Teichert's "low-level platform" and the beach ridges he estimates would have been forming since about 1000 A.D.) A further drop in sea-level somewhat later led to a localised benching at 2-3 feet above datum and after a short still-stand, the sea has slowly dropped to its present level. The advance of marine erosion in some places may perhaps suggest a slight rise during the last century.

The second type of islet reposing on the Northern Reefs is the shingle and sand cay type, of which we may take *Stick Island* (28° 53′ S., 113° 55′ E.) as a typical example.

The islet is 250 yards long and 100 yards across, rising to 12 feet above datum (see text fig. 4). It is sub-crescentic in plan, being orientated NNE-SSW, convex on the north-west, the weather side, and concave to the lee. Its perfect smoothness in outline is in striking contrast to the excessively jagged outline of the Mangrove-type islets. It has no cliffs at all and only a stunted vegetation, without mangroves.

The whole of the convex perimeter consists of a steep shingle beach rising up from the sediment-strewn reef, which grades down to about 2 feet below datum level, with extensive living coral at its fringes. The shingle beach rises up into a steep-sided beach ridge 7 feet above datum



Text fig. 4. Sketch-Map of Stick Island.

and 10 yards behind it there is an older beach ridge rising to 10 feet.

The concave side of the islet, on the other hand, is a gently sloping sand beach. On the day I visited the islet, just after a westerly gale, the two horns or spits at either tip of the crescent were both considerably elongated by accumulations of fresh sand.

Within the higher shingle beach ridge, in the south-west, there are series of low sand dunes, which may in part be old sand beach ridges. In places they rise to 12 feet. Only the outermost of these continues right up to the north-east corner, however, and in behind the shingle beach ridge in the north-west, there is a shallow depression, at about 6 feet above datum, which is floored with sandy guano with some coral boulders, and honeycombed with bird burrows.

The history of this type of islet must certainly have been fairly short. There is no definite coral which has grown in place. The older beach-ridge, however, at 10 feet above datum appears to be well beyond the capacity of present-day wave building. It may be correlated quite closely with similar ridges formed during the 5-6 foot sea-level in the Mangrove Group and Pelsart, which Teichert has regarded as dating from 1000 A.D. The seven-foot beach ridge may, for its part, be partly formed during the 2-3 foot stand and at the same time be partly contemporaneous.

(e) THE CENTRAL PLATFORM REEF, ITS ISLETS AND THE LAGOON.

At high tide, the interior of the Pelsart Group appears to be nothing but a wide lagoon, surrounded on all sides by reefs and islands, and dotted by a few scattered islets within. Observations at low tide, soundings and aerial data, however, show the position to be more complicated.

To the interior of the south-western reef, there is a broad platform, extending from end to end of that reef and inwards towards the centre of the lagoon. This platform lies mostly at about low tide level, but actually varies from 1 to 2 fathoms in depth rising in isolated islands up to 12-18 feet above datum. It is not composed of living coral, but mainly of a hard white compact limestone. This rock contains fossil corals of apparently slightly deeper-water character, including some varieties of *Favites* up to 4 feet in diameter. Delicate *Acropora* fans and branching types are notable for their absence in it. Certain pelecypod shells, such as *Katelysia*, are common. Its general appearance is one of relatively great antiquity. Extending northwards, this platform reappears as a smooth rock shelf, eroded down to about 3 fathoms, to form the basement of the westerly of the northern reefs and islets. There are some deeper channels in it, but most of this area is of fairly constant depth and consists of a smooth limestone floor with a thin layer (in places about 1 foot thick) of white calcareous sand or mud.

To the east, along the inner side of Pelsart Island, there is a similar, though narrower, shallow limestone platform and there may also be some evidence for a submerged, 3-fathom platform. In the northern part, however, around the margins of the existing platforms and rising up from the floor, there are contemporary corals growing in profusion in a zone about 6 miles long and 2 miles across. This is Dakin's

so-called "Maze" (Dakin, 1919). From the aerial photographs (see Plate III) it may be seen that this area consists mainly of an ordinary rock platform eroded into a honeycomb pattern, enclosing round "sink-holes," pot-holes, occupied by pools of fairly deep water. Dakin has already noted how many of these pools drop straight down to 15-16 fathoms. Their margins are lined by particularly luxurient coral growth, which gave Dakin the impression that they were exclusively coral, whereas there almost always seems to be a basic skeleton of older, eroded limestone. (A suggested explanation for this phenomenon will be discussed under the heading of "(g)—Reef Erosion.")

The same massive white limestone is also found rising to a height of 18 feet on East Wallaby Island (see Teichert, 1947*a*, p. 173), so here is a core of the same material as the Central Platform.

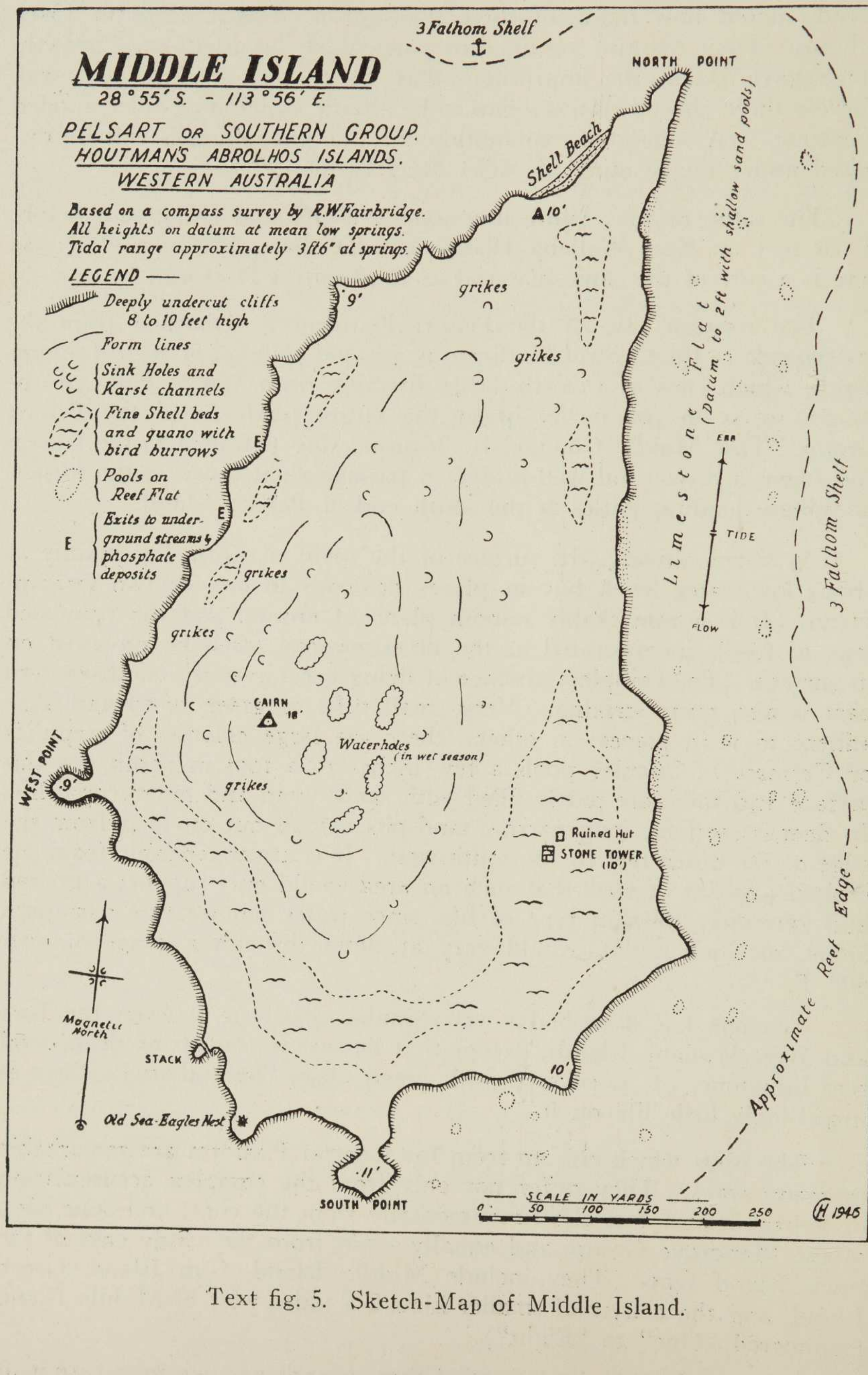
The western side of the Pelsart Platform is separated from the eastern side of the Central Platform by a broad channel of 10-15 fathoms depth, which runs in a north-south direction from Wreck Point northwards, so as to practically bisect the entire platform of the Pelsart Group. This Middle Channel is the usual ship entrance to the lagoon and forms a direct and well-protected passage right down to the former phosphate loading jetties at the south end of Pelsart Island.

As noted already, the surface of the main platform lies mainly at about low-water level, but in places descends to one or two fathoms depth. It is a remarkably smooth plane of erosion and the truncated tops of fossils incorporated in the limestone can often be observed on its surface. The complete absence of living coral over the south-western part is also quite striking. Very small tufts of green weed and algæ adhere to it in places; in others, there are large colonies of serpulids or *Vermetus*. Circular pools a few inches to a foot in depth dot this surface and these are partly filled with sand, weed and microscopic life. In deeper sections, long narrow sand-pits extend out on to it from the edge of the outer reef in the south-west. It is understandable from the ecological point of view that such an area would only support a limited and extremely tolerant type of life, since water temperature variations alone, on such a flat, would vary at times through a range of over 40° F.

Teichert has described a very similar platform between the East and West Wallaby Islands, except that he says it consists of dead coral reef limestone. It is covered with green algæ, "but otherwise there is surprisingly little life on it."

The islets which rise up from the Central Platform are remarkable in many ways. They differ not only from the complex accumulation of Pelsart Island, but also fundamentally from the coral limestone islets of the Mangrove Group, and equally again from the sandy cays of the Stick Island type. They include Middle Island, Gun Island, Green Island, and the cluster of smaller islets 2-3 miles west of Middle Island (numbered "One" to "Eight").

Middle Island is the largest of these islands and we may take it as the type example. It lies at 28° 55′ S., 113° 56′ E., and as the name



Text fig. 5. Sketch-Map of Middle Island.

implies, just about in the centre of the Pelsart lagoon, marking the western edge of the Middle Channel.

The island is almost exactly 1,000 yards long in a north-south direction and 550 yards across (see text fig. 5). Its hightest point is 18 feet above datum. In the south-east there are some ruined stone buildings, including a stone tower 10 feet high (the top is thus 20 feet above datum) from which a commanding view may be had of the whole lagoon, no part of its rim being more than 6 nautical miles distant.

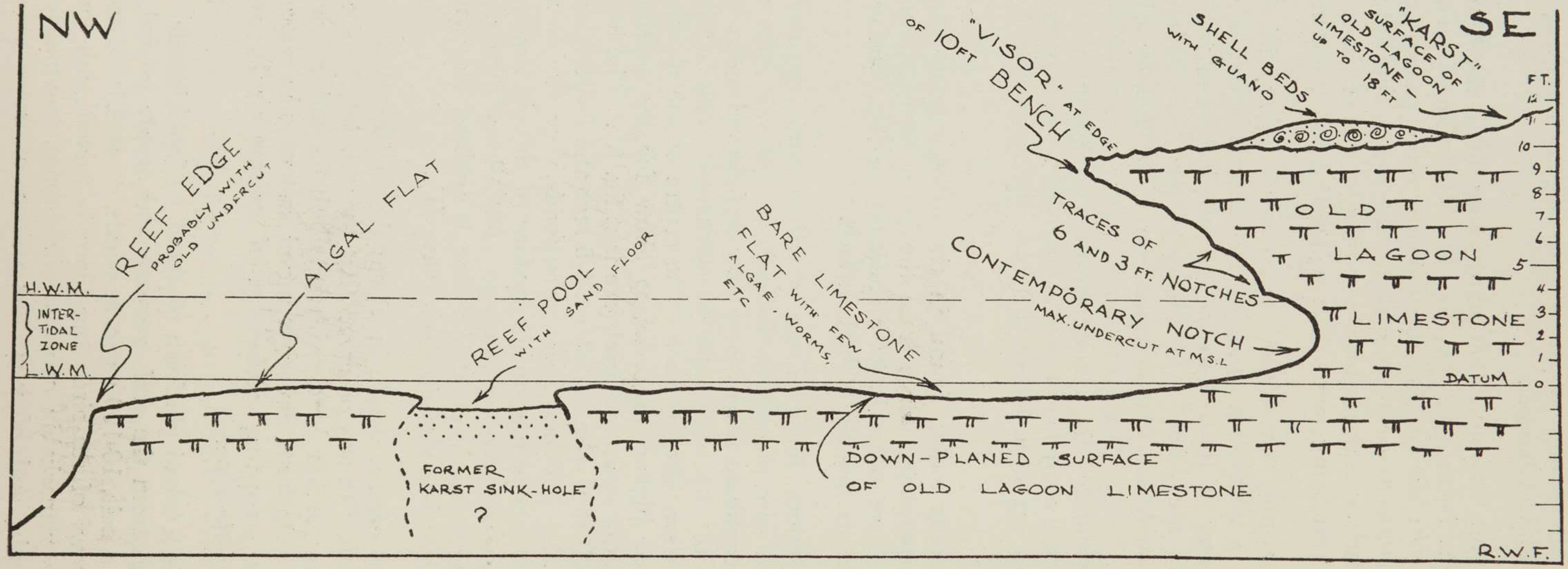
Middle Island is entirely surrounded by an overhanging cliff, 8-10 feet above datum. It is deeply undercut by the solvent action of sea-water, the notch reaching in from 6 to 10 feet in places and forming small caves. In places the visor, or overhanging part, has collapsed. The situation is very much like that described on West Wallaby Island by Teichert (1947*a*, p. 175). Wave erosion is utterly discounted since the entire island is surrounded by a wide datum-level platform, which protects the cliffs, except for small wavelets at high tide. The maximum undercut is about mean sea-level, where the rock surface is etched and pitted in the usual way.

The perfect undercut today, found in the more exposed places, is a somewhat jagged parabolic curve from the lower lip of the visor. From a distance this curve often looks remarkably perfect, but closer examination will reveal its heavily etched surface.

In less exposed sections, however, we sometimes find irregularities in this curve, which in rare places are disclosed as relics of older and higher notches. In exceptional places these may be followed up in steps. Intermediate notches of this sort may be correlated with sea-levels 2-3 feet and 5-6 feet above the present. The centre of the notch will of course be somewhat higher, in order to allow for the additional height of the then-existing mean sea-level (see text fig. 6). The heights of the older notches will thus come at above 4-5 feet and 7-8 feet above datum today. Since the 4-5 foot level corresponds very closely with the present low-limit of blackening on the surface of the old limestone, this becomes a particularly striking feature. The older, higher, and even less perfectly preserved level at 7-8 feet is without this special contrast and is relatively less obvious (see Plate II).

At the foot of the present notch, in places the surface of the platform is polished smooth. It was observed that the ebb tide performed a considerable scouring action here, with small shells and calcareous sand as the abrasives. On both the western and eastern sides there are several small beaches consisting exclusively of minute shells, mostly gastropods of the *Coxiella* type.

Above the cliffs is a broad platform of about 10 foot altitude. The margins for 5-10 yards from the cliff are bare and deeply eroded, but then to the interior is a belt, 10-100 yards in width, of shell beds, mostly riddled with the burrows of sea-birds and liberally mixed with guano. These shells are of a remarkably constant size, about one-quarter to one-half inch in length, and of very few species of gastropod and



Text. fig. 6.—Section through the reef off Middle Island. Horizontal scale greatly reduced. The basement consists of old lagoon limestone (late Pleistocene). In a few places there is a little living coral on the reef edge. The outer part of the reef is mostly covered by algae, though not generally of the coralline type, while the inner part is largely a bare surface of the old limestone, showing tuncated fossils of corals, pelecypoda etc. The reef flat is interrupted by shallow pools here and there, which may be former "karst" sinkholes. The 10 foot benched cliffs with old shell beds are relics of a mid-Recent high sea-level (10 feet above the present datum), while the undercut is notched here and there by traces of the 5-6 foot and 2-3 foot late Recent sea-levels.

pelecypod; a few small coral pebbles are included. Low scrub marks this zone.

These beds grade irregularly from almost pure coquina (unconsolidated) into grey sandy shell beds and then into a low-grade guano. Teichert appears to have observed similar shell beds on Pelsart Island, also overlying a fine-grained massive limestone and in a similar relationship to the guano. They certainly correspond exactly with his terrace of old beach deposits at 6½ feet above high-water level (*i.e.*, 6½ feet plus 3½ feet (to datum) making 10 feet, their observed level on Middle Island). Teichert recorded similar terraces corresponding to 8½ and 6½ feet above datum, and "raised" beaches of this height occur near the northern point of Middle Island. Teichert has noted that these shell species do not occur on the lagoonal flats today, and according to his estimates would appear to date from the very recent periods of higher sea-level.

Rising gently inland appears the bare limestone, with but the merest patches of soil, to form a low rise, asymmetrically placed on the west side of the island. Jointing has broken the limestone up into large, sharp-edged slabs. Its surface weathers light grey and is etched by solution channels, grikes and deep pot-holes up to 3 feet in diameter. Underground channels have collapsed in places to form small-scale karst "dolinas" up to 6 feet deep. The floors of these depressions are filled with soil. In some of the smaller ones, water collects in the wet season, and in others, tomatoes have been planted by earlier visitors, and though the fruit is small, they still make good eating.

The limestone rock-material of this Central Platform Reef and its islands has also been found by Teichert on the southern part of Pelsart Island and in the Wallaby Group, where rather similar karst features were noticed. He has called it the "Shell Limestone," to distinguish it from the essential coralline nature of the other limestones there. It is a fine-grained, fairly massive limestone, which he describes as resting on the top and in pockets in the earlier reef limestone that forms the basement of these islands. Teichert attributes it to deposition during the latter half of the Mindel-Riss inter-glacial, suggesting that a probable sudden rise of sea-level extinguished normal reef growth. (Further discussion of this correlation will be found in Section III.)

My own impression is also that there was certainly some such rise in sea-level, and that these limestones are normal lagoonal deposits. The white fine-grained matrix of nearly 99% $CaCO_3$ is typical of the white amorphorus calcareous mud which is being laid down around the lagoon today. We might, therefore, describe it more vividly as a "Lagoon Limestone."

It is notable that Teichert only found it amounting to about 3 feet in thickness, resting on a basement of coral limestone on Pelsart Island. Even here he observed: "It has the features of a lagoon deposit, but its fauna is unlike that of the lagoon shore of the present day" (*loc. cit.*, p. 162). On East Wallaby Island this shell or lagoon limestone is reported to be 6 to 8 feet thick and rests on the reef limestone at only

2 feet above high-water level. In this locality he also noticed the similarity between it and the contemporary sediments on the southern side of that island. In Middle Island, on the other hand, this limestone is measured over 18 feet in thickness and its base was not sighted. I had the impression from the nature of the karst solution, that it went down to considerable depths. This would all fit in with concept of a lagoon limestone, more or less contemporaneous in origin to the coral limestone that formed around the periphery of the group.

So much for Middle Island, and it appears to be more than likely that a similar description would fit Green Island, Gun Island, and the eight others rising from the western part of the Central Platform. It was unfortunately impossible to visit all of them, but from observation, they all appeared to have precisely the same undercut cliffs and flat limestone platforms rising from about 10 feet to 15 or more feet in the centre.

Attempting now to find an explanation to fit these curious islands, it is at once clear that they are erosion relics. In fact, there is a very small one, flat-topped, with undercut cliffs, less than 100 yards across, lying over a mile south of Middle Island. We may say that they all appear to be remnants of a once broad platform of Pleistocene lagoon limestone which extended over the whole triangle of the Pelsart Group, ranging from 18 feet above datum down to an unknown depth below. On the margins it overlaps, or interfingers, but thins rapidly over a broad rim of slightly older coral reef limestone. It may be correlated with a period of high sea-level, at least 18 feet above the present.

This platform must have been severely dissected during the succeeding glacial periods of lowered sea-level and a great part of the central platform was eroded away by a network of small streams and by one main central stream which drained the area towards the north. It is probable that during the last glacial this land was in the form of a basin-like plateau on a peninsula, about 250 feet above the sea-level then, connected to the mainland by a neck of lower country in the east. The south-east and south-western sides would have been precipitous, while drainage to the north would have reduced the topography there to a series of broad valleys.

Finally, it appears from the preliminary evidence of a series of soundings on the floor of the lagoon, which are as yet insufficiently complete as to be decisive evidence, that there were intermediate periods of still-stand in these subsequently rising sea-levels at about 3 to 15 fathoms.

(f) REEF GROWTH.

Corals are growing today, in all probability, in a continuous belt around the outer perimeter of the atoll. However, as soon as each individual colony reaches into the realm of violent wave action, it is broken off and thrown up on to the edge of the established reef and there consolidated by the activity of calcareous algæ, such as *Lithothamnium*. This appears to be a slow but relentless process, which does not fundamentally alter the outer shape of the atoll, but operates continuously in an outwards direction.

To the interior of the group, in the lagoon, however, we have observed that there are two fundamentally different types of reef. The one is "dead," an eroded limestone, while the other is living. It is with the latter that we shall deal with here. Only in the vicinity of the Mangrove Islets and the north-east part of the lagoon are there large patches of coral actually at the surface.

It appears that in many parts of the lagoon, live coral is growing up from the floor in 3-15 fathoms. Where this growth is initiated in independent spots, the corals tend to grow up in pinnacles or "coral-heads." On reaching the surface the coral growth is directed outwards to give the whole thing a mushroom shape. When this overhang becomes excessive, bits of it drop off and these help to strengthen and fill up the base.

This growth of pinnacles, or coral-heads, develops to a point where the different patches begin to unite and gradually a complete network is formed. However, by this process there are always gaps left behind and these tend to be reduced gradually to more or less narrow channels, in which coral growth is more restricted than out in the open lagoon.

In areas of active growth, such as in the Mangrove Islets, one may detect a gradual transition from the actual dry land to the massive "fringing reef," to the open network of reefs, to the large, separate coral heads and patches finally to scattered heads which do not yet even reach the surface.

Even on the apparently massive reefs not far from the shore, there can often be observed a series of narrow channels, a few inches wide near the surface or even bridged right over, which appear to widen out underneath. These appear to be "sutures" where the radiating growths from different coral patches have finally met. I have seen large segments of these overhanging coral patches which have broken off from their slender stalks and now lie tilted over at an angle of 20° or so. Coral growth is fairly meagre in these "underground" channels, through restriction of light, food supplies, etc., and it must be a matter of some time before sediments and organic debris actually fill them up. In general, these appear to be examples of what were described from Bikini Atoll as "room-and-pillar" structures by Tracey, Ladd and Hoffmeister (1946).

On the surface of the reef there are shallow depressions only a foot or a few feet deep; in these there is generally a fairly scattered growth of corals. The heads of the *Acropora* fans especially, when killed by exposure, generally bleach and soon become attached with little tassels of algæ growth. Gradually miscellaneous sediments and calcareous muds block up the whole surface of the reef so that coral growth is virtually excluded from it.

On the margins of each reef patch or platform in the lagoon there is a raised rim of debris cemented to the reef and smoothed over by calcareous algæ (see Plate I, figs. 1 and 2). This rim varies, according to the exposure, from a few inches to about 2 feet above datum, and appears to form by the heaping up of debris broken off from the grow-

ing corals of the reef edge under the influence of waves, even though in the protected lagoonal area the latter are never large. The process seems to be a perfect miniature reproduction of what goes on at the outer oceanic edge of the main reefs, where the true *Lithothamnium* Ridge is formed.

Thus by coral growth, cementing by the deposition of calcareous muds and breccia, and veneering by coralline algæ, the reef is built up, solidified and strengthened. On the shore, beach ridges will accumulate and will tend to build up the land. There can be no doubt that the serried ranks of beach ridges all around and over the surfaces of many of the islands, serve well as a protective blanket against the forces of erosion. And especially around the outer perimeters where marine solution is highly active, fresh layers of coral shingle must go far to make up for, if not totally counteract, the forces of solution.

It is true that at many points we observed, as Teichert has already (1947*a*, p. 193), how shingle material is being washed away, a feature which suggests a slight contemporary *rise* in the sea-level (for further discussion of this subject, see Section III).

But on the whole, however, the forces of erosion, even with the sea in a state of still-stand, would appear to be greater than those of accumulation. Only by repeated eustatic oscillation is the reviving breath of fresh coral growth re-introduced to provide material for island-building.

(g) Reef Erosion.

As equally as corals and associated living organisms are growing, and mechanical and chemical processes are adding bulk to the reef as a whole, a contrary set of processes are tending towards the destruction of the reef. The latter fall into three main groups:—

(i) Biological.
(ii) Mechanical.
(iii) Chemical.

An important feature of all destructive processes, however, is this: their sphere of action is mainly concentrated in the intertidal belt. Certain subærial processes will cause the decay of old coralline material above high-tide line and certain biological attack will continue a few feet below the low-tide line, while mechanical erosion by wave action is experienced down for several fathoms, but at greater depth there is no evidence of any destructive process. (It will be remembered that Sir John Murray and his followers believed that chemical solution by sea-water was the explanation of lagoons. Of such a process, there is no evidence below the inter-tidal zone.)

(i) *Biological Erosive Factors.*

In all the reefs, whether of living coral, coralline algæ or limestone, there is extensive boring, burrowing and dissolving action by various types of animal and plant. Polychaete worms play a major part; then there are the boring pelecypoda, the nibbling action of certain gastropoda, echinoids and of certain fish. It appears that certain

gastropoda (e.g., *Patella, Haliotis*) probably by some chemical action, hollow out pockets with their sucker-feet. Mayor (1924) has already demonstrated how holothuria devour enormous quantities of coral sand and reduce it to still finer particles, as well as bringing about its solution.

None of these factors by itself may seem to be of great significance, but together they combine to so loosen and expose the outer six to twelve inches or so of reef, so that the far superior forces of mechanical and chemical erosion, to be analysed below, can carry out their attacks with greater effectiveness.

The activities of these biological factors in the Abrolhos seem to be mainly restricted to the living reefs, that is to say, those of recent coralline material. The reefs of more resistant lagoon limestone appear to be remarkably poor in organic life, and on their down-planed surfaces there is relatively little evidence of biological erosion. There is some, however, as shown by occasional patches of green algæ, and by odd colonies of *Vermetus* and *Polydora*-like worms, just as described by Teichert on East Wallaby Island (1947*a*, p. 173).

(ii) *Mechanical Erosive Factors.*

On the outer edges of the reefs the relatively delicate, living coral structures are exposed to the full force of breaking waves. The effect of the latter is felt, of course, well below the low-tide limit, for several fathoms. In this way fragments of the deeper water corals are thrown up on to the reef surface. A rim of such debris tends to accumulate on the outer edge of the reef, while ridges of similar debris develop around the beach-lines.

On the reef-flat itself the larger debris is steadily reduced to the dimensions of sand, and the wave swash and tidal currents transform the send in suspension into a further, very powerful erosive scouring agent. The effect of this scour is to smooth and polish the reef rock material on the reef flat, but above mean sea-level the polishing becomes less and less apparent until by the high-tide limit no trace of it remains.

In the Pelsart Group major mechanical erosion is more or less restricted to the outer margins of the peripheral reefs, and it is only here that sand and shingle accumulations form. On the margins of the inner reefs, where the width of the lagoon permits a moderate "fetch," there is a very reduced amount of fragmentation of growing coral by wave action. Minor scouring, however, is evident over many parts of the Central Platform, where the currents set up by the rising and falling tide are an important factor.

(iii) *Chemical Erosive Factors.*

The third erosive factors are the chemical solvents, rain water and sea water. Rain water is normally a fairly acid medium which will cause extensive solution in all coral material and limestones above sea-level. Percolation of such water through these previous accumulations will continue down to base-level (which varies slightly with each tide). Solution effects are therefore produced, leading to "karst" phenomena, as noted on Middle Island and elsewhere.

Sea-water, on the other hand, is normally alkaline and represents a buffer to such solution, inhibiting further rain-water solution at the level of the prevailing tide. Nevertheless, the fact remains that there is extensive evidence of severe chemical solution within the inter-tidal limits, and of a type which is considerably more rapid even than that caused by rain-water.

These solution effects extend from low-tide level up to the limit of wave splash above high-tide, but reach a maximum almost at mean sea-level on protected shores, reaching somewhat higher at exposed points. Above mean sea-level the coral limestone is etched and pitted by the solvent to make a very jagged surface indeed. But below mean sea-level this roughness tends to be evened down by mechanical abrasion and in places where there is sand it is quite effaced by polishing.

There is no sign of solution more than an inch or two below low spring tide level. On cliffed shores there is very deep undercutting at about mean sea-level, which in places extends 10 to 15 feet under the cliff. Where the cliff itself is only 10 feet high, as is often the case, a very striking "visor" effect results.

Hitherto there has appeared no adequate explanation for the production of these solution phenomena by sea-water, though their existence has been specifically recorded in the Red Sea by Macfadyen (1930), in the East Indies by Kuenen (1933), in the Pacific by Stearns (1941, etc.), in the Great Barrier Reef by Fairbridge and Teichert (1947), and already in the Wallaby Group of the Abrolhos by Teichert (1947*a*). From personal observations, from a study of the literature, and from both ground and air photographs of a great number of Pacific coral islands examined during the Japanese War, I have concluded that these solution effects are almost universal along coasts of calcium carbonate material.

As is well known, sea-water, with a pH over 8 is normally alkaline in its effect. And in warm latitudes it is generally supersaturated in calcium carbonate (see, for example, Harvey, 1945). Theoretically, one may conclude that it is impossible for it to take more carbonate material into solution. While it is realised that in the complex chemistry of sea-water there are a great number of associated factors bearing on the subject of calcium carbonate solution, the following tentative explanation is put forward in simplified form. It has two aspects, probably complimentary, physio-chemical and biochemical, and we shall deal with the physio-chemical one first.

On the wide reef-flats, and especially at low tide, a considerable rise of water temperature has been recorded on warm sunny days. Records by Mayer at Murray Island at the northern end of the Great Barrier Reef (1918) have been paralleled by similar readings in the Abrolhos. A normal sea temperature of 19°C. will rise to 27°C. in a few hours on the reef-flat. Now, a rise in temperature causes a reduction in CO_2 solubility, and a rise in the pH. Calcium carbonate then come out of solution, being precipitated as a fine white powder. Similar observations have been made on Great Bahama Bank (Black, 1933), in the Indian Ocean reefs by Gardiner (1930), and elsewhere. Bacteria

take some part in this action, but it is not quite clear how much (Bavendamm, 1932). Large deposits of this amorphous white mud are found in all protected parts of the reef-flats (as also by Teichert on the Wallaby flat, 1947*a*, p. 173). Even in the deeper waters of the lagoon we noticed how the otherwise crystal-clear water suddenly went opaque and milky at a certain stage in the ebb tide. It appears as if with the outgoing tide suspended calcium carbonate is carried off the reef-flats and deposited on the floor of the lagoon, some even being carried out to sea.

It is now suggested that in the evening a reverse process will take place. A great reduction in temperature has been recorded in the shallows after a cold night. Under such conditions, more CO_2 is taken into solution and the pH drops sharply. From being formerly super-saturated, the water is now under-saturated and is more like an acid in respect to calcium carbonate. Solution will now take place on the clean surfaces of coral limestone exposed in the upper part of the reef-flat and undercut cliffs.

Careful temperature measurements show that only the shallow surface layers of water on the reef-flats are affected by these extreme variations in temperature. At various times on the reef-flats I have measured temperatures ranging from 27°C. down to 14°C. Beyond the edge of the reef, on the other hand, the water temperature does not change more than 1°C. or 2°C. for weeks on end. So it is only a thin layer of water nearest the shore which is endowed with this solvent property.

On *a priori* grounds one might conclude that with tidal fluctuation it would be at mean sea-level where the maximum solution effects would be found. And it is precisely at this level that the cliffs are found to be furtherest undercut. Kuenen (1933), as a matter of fact, has spoken of the "sawing" effect of the sea on the limestone cliffs at this level.

An additional factor which appears to work towards the same end as the above-outlined, purely physico-chemical one, is a biochemical one. Additional CO_2 will be liberated by reef animals at night, while during daylight this source will be more than used up by the reef plants in their photo-synthetic reactions. Revelle (1934) was even of the opinion that this was the most important factor in controlling $CaCO_3$ solubility.

In order to explain the little solution basins commonly found on most coastal limestone reefs and benches, Emery (1946) has carried out extensive tests, and has certainly shown how the pH variation (and resultant solution) is largely controlled by the CO_2 from marine algæ. While this biological factor is certainly recognised in the major problem of reef erosion, I do not consider it to be the only one—at least, in the light of my observations to date. In particular, there is no reduction in the solution effects on the cliffs of, say, Middle Island, which is one of those surrounded by wide flats of old lagoon limestone, in contrast to the cliffs around the Mangrove Islets, which are surrounded by living reefs. The old lagoon limestone flats of the Central Platform are

astonishingly devoid of life, algal or otherwise, and one may walk upon the smooth-polished limestone surface for hundreds of yards without finding more than a few hardy species. On the living reef-flats, however, there is teeming life, plant and animal, of every variety. Yet the etched and eroded limestone cliffs behind each are much the same.

An economic aspect of this contrast between the old limestone reefs and the contemporary living reefs is the way in which the Abrolhos cray-fish (*Panulirus longipes*) are almost exclusively inhabiting the live reef margins. The difference between the two types of reef, recognisable on air photographs, should have economic significance for fisheries development.

An interesting feature of the reef-flats which have been cut down out of old lagoon and coral limestone, is the occurrence of rounded "sink-holes" or "pot-holes" of large and small dimensions. They range from 1 or 2 feet across to as much as 100 yards or more across. It seems that they may either be filled with fine sediment and coarser debris, reducing them to a few feet, or even inches in depth, or they may be of considerable depth, going down many fathoms. Their margins tend to be etched out by chemical action, but the deeper ones may have a fringe of contemporary, growing coral around the lip.

From a careful study of these features on the ground and from the air photographs in the vicinity of Pelsart Island it is believed that these pot-holes cannot be of contemporary formation. Their shape, even when fringed with live coral, suggests chemical solution, from the interior of a pre-existing rock working outwards, and not the "cauliflower" pattern of living coral, which, of course, grows by accretion on to the exterior of the pre-existing reef, or upwards from the lagoon floor.

The following explanation is suggested: deep dissection of the Pleistocene-formed lagoonal and coral limestones during the last glaciation (Würm) with its low sea-level would have caused an extensive system of subaerial solution channels, caves and pot-holes to develop. With the succeeding Flandrian transgression this old karst landscape would have been drowned, permitting coral colonisation on all the old surfaces now submerged. The subsequent drop in sea-level of ten feet has led to the planation of old irregularities down to the present low tide-level, while coral now grows in profusion around the peripheries of the old karst pot-holes and depressions.

III. CORRELATION AND EVOLUTION.

As will appear by comparing Teichert's results on Pelsart and Wallaby Islands, and also at Rottnest Island, 250 miles to the south, and as I have been able to confirm at numerous points along the coast, such as Dongara, Jurien Bay, Moore River, Scarborough, Cottesloe, Point Peron and Garden Island, there is a uniformity in West Australian coastal physiographic features that demands eustatic rather than local explanation.

We now recognise, with some fair degree of confidence, three for-

merly higher sea-levels, at 10-11 feet, 5-6 feet and 2-3 feet above the present datum (low springs) which are expressed by means of eroded rock benches, undercut notches, former beach deposits and shell beds, etc.

Periods of still-stand of formerly lower sea-levels are also suggested by certain uniformities in bathymetric soundings; owing to unreliable data, and the absence of sonic sounding material in these waters, we are less sure of these figures, but 55 fathoms, 40 fathoms, 15 fathoms and 3 fathoms seem to be the particularly significant levels.

All these levels are found in, or in the vicinity of the Pelsart Group of the Abrolhos, and in addition, the formation of lagoon limestones and old coral limestones to heights over 18 feet suggests evidence for an even higher sea-level at one time, perhaps of the order of 20-25 feet above the present datum.

It might appear at first sight dangerous to attempt a long-range correlation of this material on absolute sea-level measurements alone, but the coincidence between these levels and others, measured in similar stable areas of the world, is so striking that in recent years geologists have gained some confidence in this direction. They are not identical, of course. One would not expect it so, since even the present sea-level is not everywhere geodetically constant. Unfortunately, many earlier attempts have been based on insufficient evidence, inaccurate levelling, ignorance of tidal characteristics, of exposure and erosional characteristics of the rock materials. Others again have been attempted in regions of patent crustal instability, an obviously dangerous proceeding.

I believe it is possible, therefore, to correlate these West Australian levels with those of other stable areas, and for sake of interest, I shall give an absolute dating of these Quaternary levels, suggested by Zeuner in his latest works (1945, 1946). While the subject of absolute dating is still a somewhat contested one, there now appears to be a sufficient convergence of evidence, achieved via many routes, as ably summarised by Zeuner, to make it at least interesting to correlate these dates with our sequence.

It must be pointed out, as by Teichert already, that no palæontological work whatever has been devoted to the Abrolhos Quaternary material, and so from that aspect we are completely in the dark. The field, however, is a most promising one.

Thus bearing our many limitations in mind, a review of Quaternary events in the Abrolhos may read as follows.

As is well known amongst students of the Pleistocene, the interglacial warm periods were marked by world-wide rises in sea-level. Following Zeuner (1945, p. 252), towards the end of the last (*i.e.*, Riss-Würm) interglacial, that is, about 125,000 years ago, the world sea-level stood 7.5 m. (25 ft.) higher than it is today, forming what are known in the Mediterannean as the Late Monastirian terraces. This would be an adequate level for the formation of our old lagoon and coral limestones in the Abrolhos. Teichert (1947*a*) had actually com-

pleted his MS. *before* the publication of Zeuner's book and had at that time suggested that these limestones be correlated with the earlier, Mindel-Riss interglacial, as it was one of the longest and warmest of those periods. However, the sea-level associated with this interglacial was considerably higher (forming the 100-foot Tyrrhenian terrace in Southern Europe). While, of course, it is quite possible that our oldest limestones in the Abrolhos were formed during one of the earlier interglacials, it would be necessary to assume that a very considerable thickness had been entirely eroded away by today. Furthermore, as Teichert notes (*op. cit.*, footnote to p. 187), there is this close agreement between the Late Monastirian levels and the top of the Abrolhos limestones.

With the ensuing drop in sea-level, corresponding to the Würm glaciation, the whole of the continental shelf and the Abrolhos became dry land. There appears to have been a world-wide still-stand of sea-level at about 55 fathoms (100 m.), and there is certainly evidence for a notable change in slope at or about 55 fathoms at many points along our coast. This, according to Zeuner, would have been about 115,000 years ago. As the sea rose again, probably in a series of oscillations, there appear to have been periods of still-stand at about 40 fathoms (70 m.) some 72,000 years ago, and at 15-16 fathoms (30 m.) 23,000 years ago, before the completion of the Pleistocene epoch at about 7,000 to 8,000 B.C. (*Yoldia* time), after which it rose with the so-called Flandrian transgression to more or less the present-day level by about 4,000 or 5,000 B.C.

In the regions of Northern Europe at this time occurred the transgression of the *Litorina Sea*, but Zeuner (1946, p. 104) points out that its movements were so largely conditioned by isostatic reactions there that, as a chronological or horizon marker, it is unreliable. Teichert (1947, p. 188) believes that an 18-foot sea-level corresponding with it can be recognised in the form of negro-heads above this level on East Wallaby Island, but, for myself, I was unable to find any evidence of a eustatic level of this order in the islets of the Pelsart lagoon.

In Europe there is evidence of a somewhat constant low stand of the sea at about 3-4 fathoms between 2,000 and 4,000 B.C., which is certainly interesting in view of our Abrolhos submarine platform of that height.

Oscillations of the sea both above and below its present level have clearly marked the last few thousand years. For some time there occurred the "climatic optimum" of the so-called Atlantic phase, when one would naturally expect a high eustatic sea-level, which now stood at 10 feet above the present sea-level. And at about 500 A.D. or so, according to Teichert's estimate, the 10-foot platforms cut by that sea emerged to greet the historical period.

* * * * * *

During the Würm exposure, the island must have stood up as a fairly high eminence, about 350 feet above sea-level. Deep-reaching karst erosion set in and the whole of this limestone mountain became riddled with sink-holes, underground streams, caverns, stalactite caves, and the like. It is probable that the margins of this table-topped moun-

tain were higher than the centre though the rim may well have had gaps in the north. We might compare such a terrain with that of Christmas Island today (see, for example, Andrews, 1899), or of many raised coral islands of the Pacific. In any case, a deep valley became scoured out on the northern side.

Thus, when the sea-level rose to 10 feet above its present level after the Flandrian transgression, this erstwhile mountain was almost drowned, permitting the sea to enter into the former valley and allowing corals to grow up from its floor and from the stumps of the old reefs at a great rate. Parts of the old platform were still somewhat exposed, however, and the four main areas were variously affected:—

1. The South-western Reef, exposed to the heavy southerly and westerly gales, became worn down mechanically, as well as chemically.

2. The Central Platform became mostly planed down to sea-level by chemical erosion, leaving a few relict islands behind.

3. The South-eastern Reef, being exposed to severe southeries as well as diminished south-westerly and north-westerly winds from the lagoon side, accumulated layers of shingle to form shingle ridges. These have protected it to a great extent from chemical erosion, so that it is now the main island of the group.

4. The Northern Reefs were very much dissected during the Würm erosion, but from these isolated points fresh coral grew up in new patches, radiating from the various centres in a cauliflower pattern. Shingle swept in by the north-westerly winds accumulated on top of them to help form new islets.

* * * * * *

This is where a more precise dating in the Abrolhos could begin. For this 10-foot erosion level is perfectly clear on all the older islands. It is associated with contemporary shell-beds in protected places; on the more exposed islands Teichert has described extensive systems of shingle beach ridges formed at this level.

Subsequent to the final emergence (about 500 A.D. perhaps) the sea-level has dropped step by step to its present level. At the Abrolhos Teichert had got the impression that this was a gradual process, but at Rottnest he reviewed this impression (1947*b*) having observed unmistakable traces of still-stand at 5-6 and 2-3 feet. Similar indications were noticed by Kuenen in the East Indies (1933), Crossland in the Red Sea (1907), and by other authors in many parts of the world. I, myself, have been able to confirm this at many points.

During this last emergence rapid chemical erosion in the lagoon (coupled with mechanical erosion in the South-western Reef) has kept pace more or less with the drop in sea-level, except for local relics, but in the South-eastern Reef area (Pelsart Island) and in the Northern Reef area (the Mangrove Islets) wind and sea have combined to keep up the supply of coral debris and to keep these islands above water.

4. *Islets.*

In the Pelsart lagoon, three types of islet are recognised: the old lagoon limestone type (*e.g.*, Middle Island), the younger coral limestone type (*e.g.*, Centre Islet in the western Mangrove Group), and the very youthful shingle and sand cay type (*e.g.*, Stick Island in the northern islets). In addition, there is the complex rim island, Pelsart itself, already described by Teichert.

5. *Reefs.*

In the Pelsart Group, two distinct types of reef are recognised: the living coral and coralline assemblage; and the old eroded limestone platforms, which may be cut in either old coral material or in old lagoon limestones.

An ability to identify one type from the other from the air or on air photographs is hoped to have economic value, when it is recognised that crayfish inhabit the living types of reef, but not the old eroded platforms.

6. *Winds and Growth.*

The group is believed to have been initiated as a ribbon reef, more or less coinciding with the present South-west Reef, and orientated NW-SE with incurving extremities, being very similar to the present northern Outer Barrier reefs of Queensland. Wind and wave contributed to build out cones of debris from these two wings, in north-easterly and easterly directions; these two ridges finally joined up at the north-east corner, to make an almost perfect equilateral triangle. The South-eastern Reef, however, has always tended to build up faster than the Northern, thanks to the greater southerly and south-easterly elements in the wind directions. We thus have an almost perfect triangular atoll, though today there are some gaps along the northern edge. It is probable that these gaps were cut down deeply and thus emphasised, by subaerial and fluvial erosion during the last (Würm) Glacial period, when the sea-level was probably approximately 55 fathoms below the present.

Live coral forming the source material for accretion under wind and wave, is found on most peripheral reefs, and living coral heads grow up from the floor in the northern parts of the lagoon. It is found all around the Mangrove Islets and in the "Maze" in the north-east, but is almost totally absent over large areas of the Central Platform, where physico-chemical conditions are unfavourable.

7. *Reef Erosion.*

Three aspects of reef erosion are considered: biological, mechanical, and chemical. Of the three the last is considered paramount. While the probable phenomenon of chemical solution of calcareous reef material by sea-water under special circumstances is already well recognised, a definite, though simplified explanation is now put forward. Under special physico-chemical conditions, often in company with special biochemical conditions, the amount of CO_2 in the surface waters on shallow reefs is believed to vary to such an extent that $CaCO_3$ is alternately precipitated by day from a supersaturated solution, and at

Finally, probably not more than a century ago, the sea-level ceased to drop and started to rise once more. Both new and old beach ridges are now being eroded back in places, and corals appear to be growing higher on some of the reef-flats.* Gutenberg (1941) has identified a positive 10 cm. per century rise in the universal mean sea-level by exhaustive analyses of world-wide tidal data, while Ahlmann (1946) and other glaciologists report a general recession of the glaciers and an amelioration of the polar climates during the last 100 years. Thorarinson (1940) calculated this rise due to glacial melting at 5 cm. per century, which is certainly evidence of the same order, while Marmer's tidal analyses from Baltimore (1943) show a rather larger figure for the last quarter century.

IV. CONCLUSIONS.

Detailed mapping of several types of small islands which are found in the lagoon and on the Northern Reefs of the Pelsart Group are correlated with evidence obtained by Teichert on Pelsart Island (on the South-east Reef) and in the other groups of the Abrolhos. Further observations on the reefs and submarine topography of the great central lagoon are studied in the light of the general plan and situation of the Pelsart Group near the edge of the West Australian continental shelf. Special attention is paid to constructional and destructional processes in controlling the development of the reefs. Eustatic variations in sea-level are recognised and correlated. Conclusions have been reached as follows:—

1. *Classification.*

The Pelsart Group represents, in general terms, an atoll, but it has had a very long and complex history. Its situation near the edge of a continental shelf distinguishes it geographically from oceanic atolls, but does not appear to institute any fundamental genetic difference in the reef growth.

2. *Origin.*

According to the present state of our knowledge, it appears that the building of the oldest visible reefs took place in one of the warm, late Pleistocene interglacial periods of high sea-level, the most likely being the Late Monastirian time of the Riss-Würm interglacial when the sea-level was 25 feet higher than it is today. At this time old coral and lagoon limestones were deposited. The actual birth of the reefs may well have been somewhat earlier.

3. *Later History.*

The group has subsequently suffered the experience of oscillating Pleistocene and Recent sea-levels common to stable areas in the world. Its own basement is regarded as highly stable, at least during Quaternary times. There is evidence of the mid-Recent 10-foot sea-level, as well as of two subsequent levels at 5-6 feet and 2-3 feet. These are indicated by benches, notches, shell beds, etc. . Low sea-levels during the Würm cold period are less certain, but there is some indication of levels at 55, 40, and 15 fathoms and an early Recent one at 3 fathoms.

*This contemporary rise of sea-level appears to be just as truly eustatic as the earlier changes (see my letter to the "Geographical Journal," Jan./Feb., 1947, and also one from Dr. Teichert).

night with cooling and excessive liberation of CO_2 by algæ, etc., more limestone is dissolved.

8. *Future Work.*

Clearly a very great deal more is to be learned in the Abrolhos. This may well include the following types of investigation:—

(a) Air survey: A complete air photo coverage is urgently required, for scientific, economic and charting purposes.

(b) Palæontological research: Contemporary shelly faunas requiry study and comparison with those of the earlier stages represented in the Abrolhos and up and down the coast. Valuable climatological conclusions may result.

(c) Structural: Much still remains to be done in the way of reef exploration, especially the structure of under-water reef caverns and tunnels, which probably have an important bearing on the biological environments of the area.

(d) Drilling and Geophysical work: As long ago as 1896 Saville-Kent was appealing for a deep-bore to make up for the disappointment of the Funafuti bore. It is still hard to imagine a better place for exploring the base of the reef and of the continental shelf in general than at Middle Island in the Pelsart Group.

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PLATE I.

REEF GROWTH.

Fig. 1.—General view of a shallow coral pool on the inner reef in the Mangrove Group. Tips of branching *Acropora* have been killed by exposure to spring tides and bleached. Raised algal-covered rim of reef may be seen in the middle distance beyond which is a deep channel.

Fig. 2.—The same reef flat seen from a boat in the channel. The raised algal-covered rim may be seen in the foreground. Undercut cliffs and some mangrove (*Avicennia officinalis*) form the distant shore.

Fig. 3.—A large *Euphyllia* (four feet diameter) showing "micro-atoll" structure. Growth in the centre has been stopped at some time, presumably by exposure, only to be continued all around the perimeter, where the coral has grown up higher than the centre under favourable conditions (neap tides).

Fig. 4.—A typical *Acropora* fan in a coral pool. Note how the tips of each of the higher corallites are killed and bleached by exposure.

All the above photographs (by the author) were taken at low spring tide.

Fig. 1.

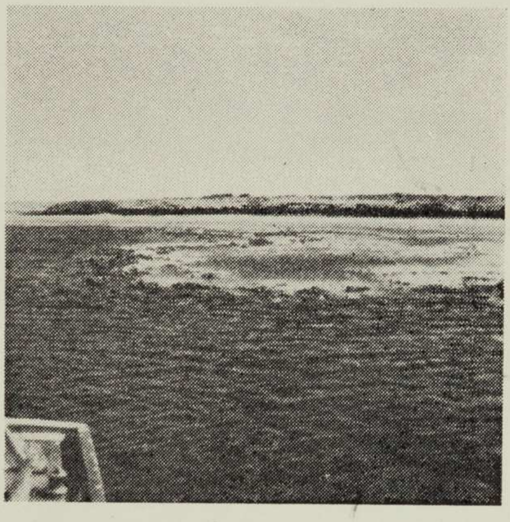

Fig. 2.

Fig. 3.

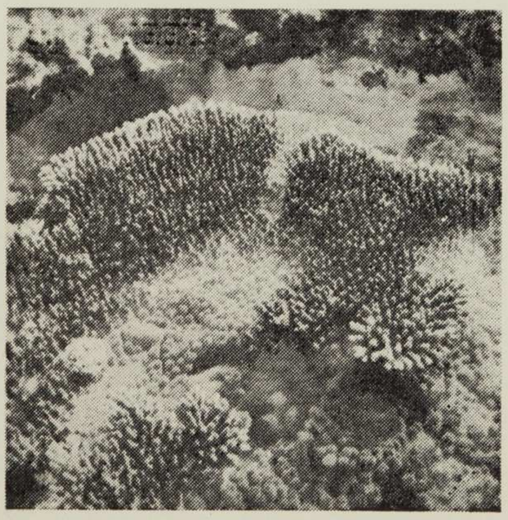

Fig. 4.

REEF LIMESTONE EROSION.

On the north-west side of Middle Island looking south-west. Typical undercut cliffs in the 10 foot lagoonal limestone. The upper surface of the latter is etched and eroded by rain-water solution, while its foot is undercut by sea-water solution. Note remnants of double notch and blackening above high tide line. Very little mechanical erosion occurs here as the shallow protecting reef-flat is several miles wide. The shallow reef-flat, seen below six inches of water, nearly at low tide, has no living coral, but is eroded out of a similar lagoonal limestone as the island. (Photo by the author).

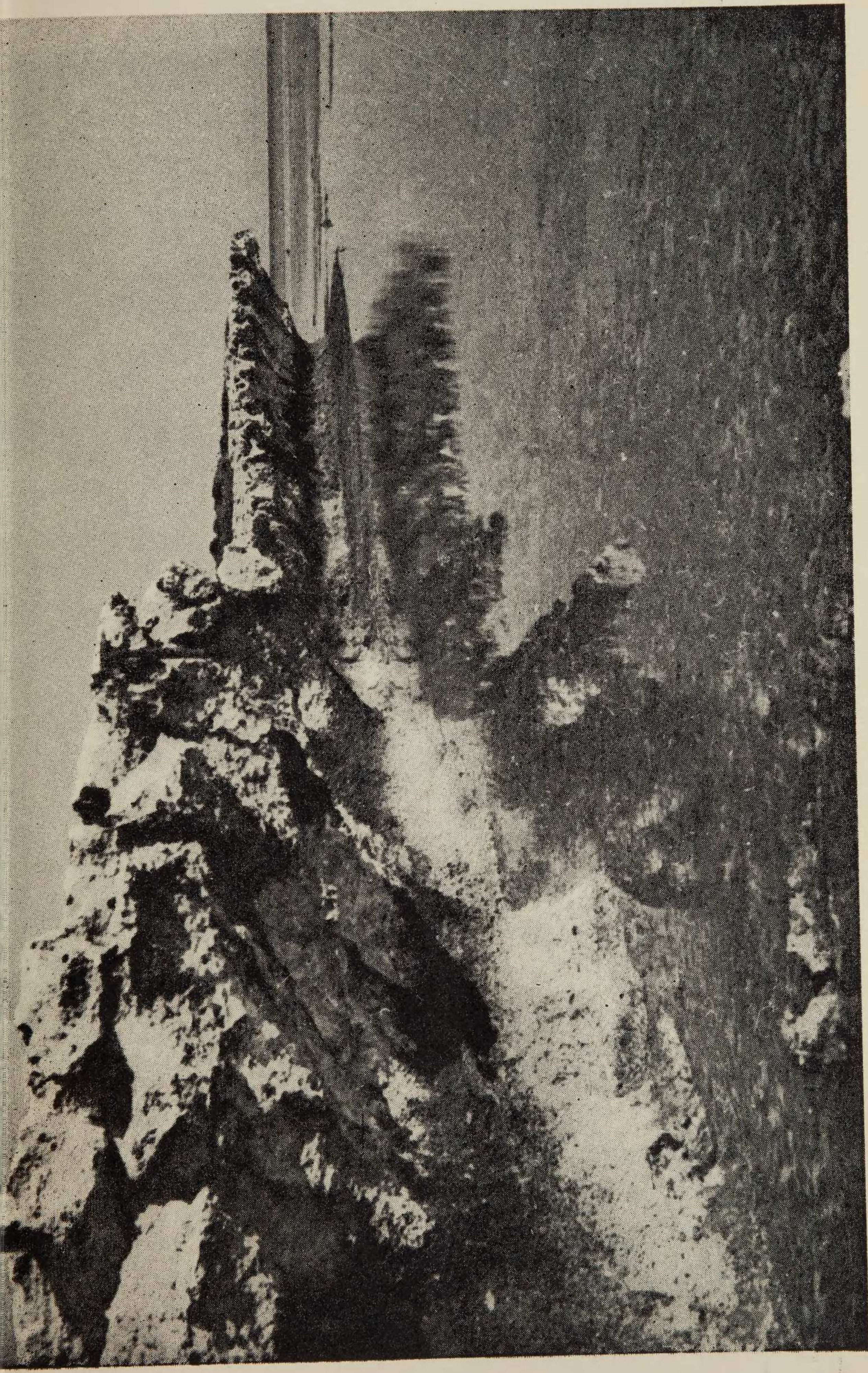

PLATE III.

ERODED REEF FROM THE AIR.

The "Maze" at the north end of Pelsart Island. The living coral here appears only as a marginal fringe on the deeply indented margins or around pot-holes in the old coral or lagoon limestone platform which has been exposed at periods of low sea-level to severe erosion and is now almost submerged again. (Photo by R.A.A.F.)


N
CALCAREOUS MUD
MANGROVE
BEACH RIDGES
THE MAZE
LIVING CORAL
DEEP POT-HOLES
PELSART ISLAND
REEF FLAT
SEDIMENT-COVERED
FILLED POT-HOLES
SCALE IN YARDS
0 100 200 300 400 500 600